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Glacier changes and climate trends derived from multiple sources in the data scarce Cordillera Vilcanota region, Southern Peruvian Andes

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Abstract

The role of glaciers as temporal water reservoirs is particularly pronounced in the (outer) tropics because of the very distinct wet-dry seasons. Rapid glacier retreat caused by climatic changes is thus a major concern and decision makers demand urgently for regional/local glacier evolution trends, ice mass estimates and runoff assessments. However, in remote mountain areas, spatial and temporal data coverage is typically very scarce and this is further complicated by a high spatial and temporal variability in regions with complex topography. Here, we present an approach on how to deal with these constraints. For the Cordillera Vilcanota (Southern Peruvian Andes), which is the second largest glacierised Cordillera in Peru (after the Cordillera Blanca) and also comprises the Quelccaya Ice Cap, we assimilate a comprehensive multi-decadal collection of available glacier and climate data from multiple sources (satellite images, meteorological station data and climate Reanalysis), and analyze them for respective changes in glacier area and volume and related trends in air temperature, precipitation and specific humidity. In general, the climate data show a moderate (compared to other alpine regions) increase in air temperature, weak and not significant trends for precipitation sums, and an increase in specific humidity at the 500 hPa level. The latter is consistent with observed increase in water vapour at the tropopause level during the past decades. It is likely that the increase in specific humidity played a major role in the observed massive ice loss of the Cordillera Vilcanota over the past decades.

1 Introduction

Mountain glaciers are a major fresh water resource for people living in, nearby or in the adjacent lowlands of mountain ranges (Barnett et al., 2005). Observed worldwide glacier retreat is thus an important concern for the availability of fresh water in these areas. In the tropics, late 20th century glacier retreat has been observed to be particularly pronounced (IPCC, 2007). Moreover, because of the distinctive outer tropical

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hydrological seasonality, which is characterized by one dry and one wet season (Kaser, 2001), glacier melt water often provides a critical source of fresh water in these regions during the dry season (Bradley et al., 2006, 2009).

While the observed global mean trend for glacier retreat is clear, the significance varies between regions and locations (WGMS, 2009). An adequate spatial and temporal coverage of measurements is required to derive trends for a specific region or single glaciers. However, most mountain regions worldwide and particularly the tropics lack continuous (long-term) measurements of glacier mass balance and/or climate variables. Nevertheless, as outlined above, particularly in these regions, implementation of adaptation measures to reduce adverse impacts of climate change requires decision and policy makers to be informed of regional/local glacier and climate trends. The science community is therefore challenged to provide estimates and assessments of trends and scenarios for regions with incomplete or weak data. Adequate approaches need to be developed and applied that can deal with incomplete data and allow for robust trend estimations of glacial and climatic changes and related impacts for specific regions.

This study focuses on the data scarce area of the Cordillera Vilcanota (CV) in the Southern Peruvian Andes. The CV is the second largest glacierised mountain range in Peru, and also comprises the Quelccaya Ice Cap (QIC), which is the largest tropical ice cap on Earth. The glaciers of the CV provide water for the relatively densely populated Cusco region. For the CV, only very few long-term (decadal-scale) climate and glacier data are available. This is remarkable in view of its size and socio-economic importance (e.g. Vergara et al., 2007), and also in contrast to the Cordillera Blanca (Central Peru), where several glacier measurement and observation programs were initiated during the past decades and are still running (e.g. Ames et al., 1989; Kaser et al., 2003).

In this study, we present an approach that allows providing a regional baseline for climate and glacier trends for the data scarce area of the CV. Past time series of observations and measurements from multiple sources, which are often made for reasons others than providing climatic baseline data, are collected, quality checked, homogenized and analysed. The results eventually can serve to inform decision makers who are initiating climate change adaptation measures. The approach possibly also provides a blueprint for studies in other regions with similar challenges.

The paper starts with a description of the CV area (Sect. 2) and continues with a review of glacier and climate data from multiple sources available for this region, including inventories, satellite and GPR data for the glaciers and station and Reanalyses data for the climate (Sect. 3). The data are then prepared to serve as a baseline for consequent change assessments and trend analyses (Sects. 4 and 5). Finally in Sect. 6, the results are critically discussed and causally related.

2 Study area: Cordillera Vilcanota – Quelccaya region

The CV is located in southern Peru (about 14° S/71° W) in the Region Cusco, at the eastern margin of the Andes where it marks the highest elevation above the Amazon basin. The glacierised mountain range is arc-shaped, extending some 60 km east-west, and encompassing a high plateau region at about 4500 m a.s.l. and above. The most striking landscape feature of this altiplano region is the Laguna Sibinacocha, a 15 km long glacial lake that is used for hydropower generation. The highest peak of the mountain range is Nevado Ausangate (6384 m a.s.l.) and glacier tongues currently terminate at about 4700 to 5000 m a.s.l. The QIC is the largest tropical ice cap on Earth and situated at the south-eastern margin of the CV. It has been extensively studied in the context of climate-glacier interactions, starting in the 1970s (Hastenrath, 1978; Thompson et al., 1979). Thompson and colleagues drilled the first ice cores in tropical regions at Quelccaya and unfolded paleo-climate and glacier history (e.g. Thompson et al., 1984, 1985).

The drainage system of the CV is relatively complex, with glaciers draining into Río Paucartambo and later Río Urubamba and the Atlantic ocean towards north and north-west, into Río Vilcanota and later Río Urubamba and the Atlantic towards south and

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northwest, Río Corani, San Gabán and the Atlantic towards northeast, and into Lago Titicaca towards southeast (Fig. 1). Socio-economically, Río Vilcanota, fed by the glaciers of CV is an important river in the region and used for hydropower, agriculture and household consumption.

Other than those carried out on the QIC, there are very few glaciological studies available for the CV region. This is remarkable given that this is the second largest glacierised mountain range in Peru (following the Cordillera Blanca) and given its importance for local and regional freshwater, irrigation and hydropower. Morales-Arnao and Hastenrath (1999) provided an estimate of the glacier area for 1975 (579 km^2), and Mark et al. (2002) presented a paleo-glaciological study for the western part of the Cordillera. Huggel et al. (2003) assessed glacier changes between 1962 and 1999 but only for a smaller part of the mountain range, i.e. those glaciers draining into Río San Gabán towards northeast. They found that the glacier area has been reduced by as much as 48 % during this period (from 52.8 km^2 in 1962 to 27.6 km^2 in 1999). A comprehensive study on recent glacier changes in the entire CV, however, is still lacking.

The CV is situated in a climatologically complex zone, influenced by tropical and extra tropical upper level large-scale circulation as well as synoptic-scale systems (Garreau, 2009). During the wet season, the CV lies at the northern boundaries of the Bolivian High and is thus mainly influenced by easterly flow that extends to 21° S. During the dry season, easterly flow continues to predominate, while the subtropical westerly jet also influences the region (Garreau, 2009). Low-level flow transports most of the water vapour and thus controls precipitation, adding even more complexity. The high altitudes of the CV remain very dry during most of the year because of the low temperatures, low air density and high radiation. Only convective storms and moisture transported from the Amazon basin by upper level easterlies lead to significant precipitation between December and March (Vuille et al., 2008; Falvey and Garreau, 2009). The CV region is further also influenced by interannual variability patterns caused by the El Nino – Southern Oscillation (ENSO).

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Given this climatological pattern, accumulation on the CV glaciers is mostly limited to austral summer months, while different ablation processes (melt and sublimation) are active all-year round.

3 Available observational data

3.1 Glacier data

3.1.1 Glacier inventory (aerial photographs)

The national glacier inventory of Peru is the first region-wide catalogue of glaciers. It is based on aerial photographs and includes complete coverage of the CV for 1962 (Ames et al., 1989). The inventory provides information on geographic location, minimum and maximum glacier elevation, glacier width, length and area, and aspect for each of the about 460 glaciers of the CV.

3.1.2 Satellite images

For the present study Landsat-TM5 satellite images from 25 July 1985, 23 July 1996 and 4 August 2006 were acquired. The spatial resolution of the images is 30 m. Landsat-MSS images from this region exist from the mid-1970s but were not used here due to their reduced spatial resolution. The Landsat images from 1985, 1996 and 2006 represent favourable conditions for glacier mapping and, together with the glacier inventory data, they allow for an assessment of glacier changes spanning more than half a century.

For studying changes of the QIC at higher temporal resolution, additional Landsat images of 1975, 1991, and 2000, as well as ASTER images of 2004, 2006, 2008 and 2009 were used. These images were all taken during dry winter season between end of May and beginning of August.

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As a topographic basis the SRTM-3 digital elevation model (DEM) at 90 m spatial resolution and the ASTER GDEM at 90 and 30 m spatial resolution, respectively, were used. Vertical errors of SRTM are ±16 and ±6 m for absolute and relative accuracy, respectively (Rabus et al., 2003). For the ASTER GDEM, a vertical error of 20 m at 95 % confidence level is provided officially (ASTER Validation Team, 2009) but some studies have stressed the partly large errors of this DEM (Reuter et al., 2009).

3.1.3 Ground Penetrating Radar data

In addition to the more generally available inventory and satellite data listed above, for the current study also Ground Penetrating Radar (GPR) data were available. The GPR campaign was performed on the QIC in 2008 to assess the thickness of ice along a transversal profile (Fig. 2). A Narod Geophysics type georadar transmitter with 5 Mhz antennas and oscilloscope receiver was used. Data were collected at 10 m spacing along a single transect and all points were georeferenced using a hand-held GPS receiver (accurate to about 5–10 m). The transect was approximately 2.3 km long, beginning at the ice cap summit and extending west towards the margin. A two-way travel time was calculated from the first reflection off the bed, and translated this travel time to an ice depth using a constant radar velocity of 0.168 m ns^{-1}. Based on this velocity, a 1/4 wavelength resolution of 8.4 m was calculated.

3.2 Climate data

3.2.1 Meteorological stations

The National Meteorological and Hydrological Service of Peru (SENAMHI) maintains a network of climate stations in the Cusco area. Several records start as early as 1965, but many stations were shut down in the meantime, most have several major data gaps and a lot of the stations had even been out of order for several years during the politically unstable time in the 1980s. There are 30 stations located in the area of the CV at altitudes above 4000 m a.s.l., and several of them even above 4300 m a.s.l., nearly corresponding to the elevation of lowest glacier termini of the CV. All climate stations provide measured air temperature at 07:00/13:00/19:00 PET, minimum and maximum air temperature and daily or semi-daily precipitation sums. A small number of stations also provide other variables, including dew point, air pressure or wind velocity and direction. In addition, there are also some precipitation stations in the area.

3.2.2 NCEP/NCAR Reanalysis

In remote high-mountain regions, and generally in data-scarce areas, global reanalyses are often the only continuous long-term data series available. They provide a continuous stream of three-dimensional fields of meteorological variables of the past through advanced data-assimilation techniques of available observations (Bengtsson and Shukla, 1988). The space and time resolution of the generated data is determined by the model. It is furthermore independent of the number of observations, because areas void of observations are filled with dynamically and physically consistent model-generated information (Bengtson et al., 2004).

Here, we use the NCEP/NCAR Reanalysis 1 (see Kalnay et al., 1996), a global reanalysis with a horizontal resolution of T62 (about 210 km), 28 vertical layers and with a record starting in 1948. The variables six-hourly, daily and monthly averages are provided. We use four grid boxes from the Cusco area (10–15° S; 75–70° W) for air temperature and specific humidity, where the latter variable influences the energy balance of tropical glaciers significantly (Kaser, 2001).

4 Methods

4.1 Glacier changes (area and volume)

4.1.1 Glacier area estimation

Satellite images have been extensively used for the assessment of glacier areas. Successful results have been achieved with Landsat-TM data using the image ratioing method by dividing band TM4 by TM5 (Paul et al., 2002; Raup et al., 2007). This method has also been applied in this study. For glacier mapping in the Cordillera Blanca (Peru), Racoviteanu et al. (2008) and Silverio and Jacquet (2005) used a Normalized Difference Snow Index (NDSI). In a methodological study on QIC, Albert (2002) showed that results from the NDSI and the TM4/TM5 method yield a difference of only $\sim$2 % in glacier area.

Through all periods of glacier mapping, including the 1962 inventory, debris covered glacier parts were not considered. Because of the typically steep slopes and high altitudes in the study area, debris cover is of little importance in the CV. Consistency of methods is thus maintained over the analyzed period.

4.1.2 Glacier volume estimation

Volume estimates for glaciers are difficult and fraught with considerable uncertainty, in particular for larger unmeasured regions. A popular yet debated method applies scaling laws between area and volume, based on calibration from measured glaciers (Bahr et al., 1997). More recently, methods have been developed to compute ice thickness along glacier flow lines and volume estimates based on thickness interpolation algorithms (Farinotti et al., 2009; Linsbauer et al., 2009). These studies found that thickness estimates typically lie within an error range of 20–30 %.

Here, we used an approach based on Haeberli and Hoelzle (1995), using glacier inventory parameters to estimate ice thickness and volume. The average ice thickness

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h_f along the central flow line can be expressed as:

$$h_f = \frac{\tau}{f\rho \cdot g \cdot \sin \cdot \alpha} \quad (1)$$

Where τ = mean basal shear stress along the central flow line, f = shape factor (taken as 0.8 for all glaciers); ρ = density of ice (900 kg m^{-3}, as an average value based on field data from other glaciers in Peru) ; g = gravitational acceleration (9.81 ms^{-2}); α = average surface slope of the glacier. Basal shear stress is commonly considered to vary within 0.5 and 1.5 bar (Paterson, 1994), with values of ~1 bar as a first approximation and average for valley glaciers (Binder et al., 2009). Haeberli and Hoelzle (1995) presented an empirical relation between τ and ΔH, the difference between maximum and minimum glacier elevation. However, this relationship is established primarily from a dataset of mid-latitude glaciers. Little is known about the basal shear stress values of tropical glaciers, which are generally characterized by high mass balance gradients (Kaser and Osmaston, 2002; Huggel et al., 2003) and relatively small ΔH. For the 1962 glacier inventory data of the CV region, we calculated a mean ΔH of 412 m, with a standard deviation of 282 m. Based on that and the relationship after Haeberli and Hoelzle (1995) we assessed a reasonable range of average basal shear stress of $0.8 \leq \tau \leq 1.2$ bar. For QIC, where we have GPR ice thickness measurements (see Sect. 3.1.3) available for validation, we performed several calculation runs using the indicated range of τ and found best agreement of modelled and measured ice thickness for $\tau = 1.2$ bar (see also Sect. 5.1). However, to account for variations of mean basal shear stress on the different glaciers and to generally increase robustness of results, we also assessed ice thickness (and volume) by using $\tau = 1$ bar. Eventually, to calculate the average ice thickness for the entire glacier based on the ice thickness h_f along the central flow line, h_f is multiplied by $\pi/4$, assuming a semi-elliptical cross-sectional glacier geometry (Haeberli and Hoelzle, 1995). Ice volumes then simply result from calculated ice thickness and respective glacier areas.

The ice thickness estimates for 1962 were based on the corresponding glacier inventory data and the application of Eq. (1) for every single glacier, using $\tau = 1$ bar

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and $\tau = 1.2$ bar. The ice thickness estimates for 2006 were based on five representative glaciers only, using the area information provided by the aforementioned satellite images. The ice thickness difference between 1962 and 2006 was calculated using Eq. (1). The average thickness reduction was found to be between 10 and 20 % for this 40-yr period. Accordingly, we applied a thickness-volume scaling using a thickness reduction of 20 % for the 1 bar case, and a 10 % thickness reduction for the 1.2 bar case, in order to provide a lower and upper estimation of ice volumes for 2006.

4.2 Preparation of climate records for trend analyses

Reliable climatic trend analyses require long-term, quality checked and homogenized climate time series to avoid trends caused by non-climatic factors (Begert et al., 2005).

In the frame of an ongoing climate change adaptation programme (PACC; Salzmann et al., 2009) a large number of the time series from the meteorological stations in the Cusco and Apurimac Regions and the neighbouring areas have been quality checked (Schwarb et al., 2011). As aforementioned, most of the records, however, are not long enough or continues to allow for reliable trend analyses. Therefore, we have reconstructed one continues, long-term time series of one station to enable subsequent trend analyses for the CV area. For the reconstruction we have chosen the station Santa Rosa (−14.6° S/−70.8° W), which is located at 3940 m a.s.l., and among the closest stations to the CV. Data gaps (the years between 1965–1994 for air temperature, respectively between 1965–1970 and 1981–1989 for precipitation) have been reconstructed by using a number of nearby stations, situated within a radius of about 80 km from Santa Rosa (see Fig. 1): Ayaviri (3920 m a.s.l.), Chuquibambilla (3950 m a.s.l.), Llally (4190 m a.s.l.), Progreso (3965 m a.s.l.) and Pucara (3910 m a.s.l.). For precipitation, the station Nuñoa (4135 m a.s.l., at about 20 km distance from Santa Rosa) was additionally considered. From each of these stations an estimation value for Santa Rosa was calculated using linear correlation, based on common observation time series. A minimum of two observations per month (for air temperature), or three (for total precipitation sums), was used from the nearby stations. The arithmetic mean of all estimation values was then used as the reconstructed monthly air temperature mean and monthly total precipitation sum for the station Santa Rosa.

The NCEP/NCAR Reanalysis provide data at different sigma levels. The upper, glacierised parts of CV are located at an altitude of around 5600 m a.s.l. Because this is close to free-atmosphere conditions, here, we used the 500 hPa atmospheric level corresponding to about 5850 m a.s.l. of the NCEP/NCAR Reanalysis, instead of the NCEP/NCAR surface height fields at around 3500–4000 m a.s.l. for the CV area. Regarding record length, the NCEP/NCAR Reanalysis provide in principle data since 1948. However, before the Geophysical Year in 1958, only very few radiosonde measurements were taken in the southern hemisphere (e.g. Chen et al., 2008). Because radiosonde data are a primary input for the free atmosphere data in Reanalysis, the homogeneity of specific humidity in the upper-level troposphere in Reanalysis must be questioned for the years before 1958 (Paltridge et al., 2009; Chen et al., 2008). For specific humidity, thus we only used data since 1958 in our study. Although we are aware that there is again a step towards increased homogeneity since 1979 due to the assimilation of satellite observations (Bengston et al., 2004; Vey et al., 2010), for the following analysis we will use the Reanalysis between 1958 and 2009.

On these prepared continuous long-term time series, we calculated temporal trends using simple linear regression and provide the trend magnitudes and the estimates of significance. We consider the trends to be statistically significant if the p-value is smaller than 0.05.

5 Results

5.1 Glacier changes (area and volume)

Over the entire glacierised area of CV, our results indicate that glaciers have changed only marginally between 1962 and 1985 (Table 1). Between the mid-1980s and the mid-1990s, however, 100 km^2 of ice has been lost, corresponding to a 23 % reduction since 1985. The following ten years until 2006 continued to show strong glacier retreat, yet at a lesser rate than during the previous ten years. Over the two-decadal period a reduction of 14 % is observed compared to 1996 and a reduction of 33 % compared to 1985 (and 1962).

The more detailed data available for the QIC and the Qori Kalis outlet glacier show that the individual glacier behaviour corresponds well to the greater picture of the entire CV (Table 2). As for the rest of the mountain range, the QIC area did not significantly change between 1962 and 1985. The strong glacier retreat started there also in the mid 1980s. The total glacier area of Quelccaya was reduced by 23 % between 1985 and 2009, a somewhat lower value than for the overall CV.

In terms of ice volume loss it is clear that it also must had been very strong over the past two decades, irrespective of the uncertainties involved in volume estimation. For 1962, our estimates suggest an ice volume in the order of 17 to 20 km^3. For 2006, the corresponding range is 9.2 to 12.4 km^3, resulting in a volume loss of about 40–45 %. Since glacier area did not change much between 1962 and 1985, volume losses likewise must have taken place primarily since the mid-1980s.

For validation of the modelled ice thickness, we used ice thickness measurements from the GPR campaign on QIC in 2008 (Fig. 2). Measurements show an ice thickness maximum of approximately 150–170 m in a slight overdeepening near the summit. Enhanced scattering is evident in the second half of the radar transect (beyond ~1200 m horizontal), and may be the result of increased meltwater in the surface snowpack or underlying ice. Despite this increased scattering, bed reflections are apparent and show decreasing thickness towards the ice cap margin, reaching a minimum value of approximately 50 m at the end of the transect and the margin of the ice cap. Measurements in 1978/79 on QIC by Thompson et al. (1982) show maximum ice thickness of about 180 m in the saddle between the summit and the North domes, which support our results.

For the north-western side of the ice cap with Morojani and Morojani-2 glaciers (Fig. 2) GPR measured average ice thickness is about 90 m. For the corresponding sites on the two glaciers, from the summit of the ice cap to the glacier terminus, Eq. (1) indicates average ice thickness between 75 and 99 m, depending on glacier and shear stress value. As mentioned in Sect. 4.1.2 best agreement was found for $\tau = 1.2$ bar.

5.2 Climatic trends

For air temperature, both station and NCEP/NCAR Reanalysis data, show positive trends for the analysed time windows (Figs. 3 and 4), with, however, different significance levels. Figure 3 shows the linear trends for minimum and maximum air temperature. A clear positive trend (p-value = 0) is found for maximum air temperature (Fig. 3b), while the trend for minimum air temperature (Fig. 3a) is weak and not significant. Because of the distinctive seasonality (cold-dry and warm-wet) in the study area, which influences the glacier regime significantly, trends were also calculated for seasonal means. For maximum air temperature, we found positive and significant trends (except for DJF) for all seasons (Fig. 3d, Table 4). The trend for minimum air temperatures (Fig. 3c, Table 3) shows only a slight increase during DJF and SON, and no trend (not significant) during MAM, and a negative trend (not significant) for JJA.

The monthly mean air temperature trends from the NCEP/NCAR Reanalysis (Fig. 4, Table 5) show good agreement with the station data. There is a significant positive trend for all seasons, with absolute changes in the same ranges as for Santa Rosa station. Note, however, that the absolute changes for the Reanalysis data span 12 yr more (data since 1948).

For seasonal precipitation sums, the station Santa Rosa (Fig. 5, Table 6) shows slight negative linear trends for all seasons, however, they are only significant during SON. Changes for precipitation are thus not as obvious as for air temperature.

Specific humidity from the NCEP/NCAR Reanalysis shows a significant, positive, linear trend for all seasons (Fig. 6, Table 7). Unfortunately, there are no reliable station data for specific humidity available in the region that could be used for cross-checking. On a larger geographical scale, however, Vuille et al. (2003) provide evidence for a positive humidity trend for the Central Andes, in both the CRU dataset (1950–1994 and 1979–1995) and the ECHAM4-T106 climate simulation for 1979–1998.

6 Discussion

6.1 Glacier area and volume change

The observed changes and rates of changes in glacier area and volume of the CV are very high, particularly since mid 1980s and compared to numbers from the European Alps. While we found a reduction of area of about 30 % and of volume of about 40–45 % between 1985 and 2006 for CV, Zemp et al. (2006) report for the period between 1975 and 2000 a reduction of glacier area of about 22 % and of volume of about 30 % for the European Alps. The stronger retreat pattern of the outlet glacier of Qori Kalis compared to the ice cap, including an earlier onset of accelerated glacier retreat, is likely related to the formation of a glacier lake at the glacier terminus, and the different hypsometries (Mark et al., 2002). Our results on glacier changes in the CV corroborate findings from other glacierised Cordilleras in Peru, but also add new insights. The Cordillera Blanca is by far the most studied glacierised Cordillera of Peru, both historically and at present. Consistent with our results for CV, studies from the Cordillera Blanca reveal little change between 1970 and 1986 (Georges, 2004; Silverio and Jacquet, 2005). Studies in the Cordillera Blanca furthermore indicate that the 1930s and 1940s were characterized by significant glacier loss, resulting in growth and formation of many glacier lakes, with severe disasters due to lake outburst floods (Carey, 2005). There are no corresponding documents available for this period for the CV, probably due to its remote location.

For both Cordilleras of Peru, the strong recent glacier shrinkage has likely started in the second half of the 1980s. The glacier shrinkage in the CV appears to have been somewhat stronger than in the Cordillera Blanca. While a reduction in area of 12–22 % between 1970 and 2003 is reported for the Cordillera Blanca (Racoviteanu et al., 2008), corresponding values from the CV are approximately 30 % higher. It should be noted that there is one reference (Morales-Arnao and Hastenrath, 1999) that indicates for the CV a glacier area of 579 km^2 for 1975. This is much higher than our relatively constant values found between 1962 and 1985 of 440 and 444 km^2, respectively. However, this is likely due to a differently defined spatial domain of the CV area in their study compared to the present one), or due to reduced accuracy of the lower-resolution Landsat-MSS satellite images used for the study in 1975.

There are very few glacier volume change estimates available for other mountain ranges in Peru. Mark and Seltzer (2005) assessed volume changes for three individual glaciers in the Cordillera Blanca between 1962 and 1999. Their estimates are broadly consistent with ours. For Nevado Coropuna, an ice-capped volcano 270 km southwest of the CV, in a much drier climate, Peduzzi et al. (2010) estimated an ice volume of 4.62 km^3 for the 2000s with an average ice thickness of 81 m and an error margin of about ±20 %, using a statistical relation between ice thickness, elevation, slope and aspect. While a reduction of glacier area of 60 % was mapped for the period 1955–2008, there was a 18 % loss estimated for the corresponding volume. However, the glacier area reported by Peduzzi et al. (2010) for Cordillera Coropuna in 1955 (122.7 km^2) is probably about 40 km^2 (or 48 %) too large due to strong snow cover on aerial photographs (P. Peduzzi and W. Silverio, personal communication, 2008). According to the data from Peru's glacier inventory (Ames et al., 1989) the area of the glaciers on Nevado Coropuna was 82 km^2 in 1962 (see also Racoviteanu et al., 2007). Peduzzi et al. (2010) furthermore indicate a glacier area of 80.1 km^2 for 1980, followed by strong retreat resulting in an area of 65.5 km^2 by 1996. Hence, by correcting the figures for the 1950s/1960s for Coropuna from 122 to 82 km^2, a consistent pattern of glacier changes from north to south Peru is found, which shows that glacier areas were relatively stable between the 1960s and 1980s, followed by a period of strong glacier retreat that continues until today. This is notable because the three Cordillera regions (i.e. Cordillera Blanca, Vilcanota, Coropuna) are under the influence of considerably different climatic regimes.

It is widely recognized that regional glacier volume estimates are associated with large uncertainties, due to the inability to directly and precisely measure the ice dimensions, and the need to extrapolate ice thickness by using semi-empirical formula. Likewise, we made our used assumptions explicit. In our modelling approach, the basal shear stress is a sensitive parameter for the volume estimates. Yet, we evaluated our modelled shear stress using GPR ice thickness measurements on the QIC to constrain a reasonably appropriate value. Confidence in our estimates furthermore is given by a recent study on Jostedalsbreen ice cap in Norway, where found shear stress values are similar to ours on Quelccaya (Meister, 2010). To our knowledge, there are no other references of estimates of basal shear stress for tropical glaciers available, and consequently, a range of uncertainty of about 20 % needs to be considered. We therefore used different values to indicate the likely range of ice volume.

Similarly, for mid-latitude glaciers, recent modelling studies computing ice thickness along glacier flow lines indicate error ranges of 20–30 % (Farinotti et al., 2009; Linsbauer et al., 2009). Another approach using measured length changes showed that modelled glacier volumes may be within a 30% error margin in a reasonable case, but in less optimal cases may vary as much as several factors (Lüthi et al., 2010).

In summary, we accept that our absolute volume estimates for each time step are uncertain, but the relative ice volume change between time periods is robust and plausible given the vigorous loss in area.

6.2 Climatic trends

Based on the data used in our study, there is a significant linear air temperature increase found since the 1950s and 1960s, with greater changes for maximum than for minimum air temperature, and a slight negative (non-significant) trend for precipitation. These findings correspond with results from other studies in this region (Vuille et al., 2003; Francou et al., 2003). However, compared to air temperature trends in other mountain regions such as the European Alps (Begert et al., 2005; Auer et al., 2007) the trends for the CV are relatively small, nevertheless consistent with continental-scale analyses (IPCC, 2007).

In order to account for data inhomogeneity and uncertainty inherent to our remote setting, and to reduce uncertainties, we used a multi-data-source approach and preprocessed the data adequately prior to their use. The general agreement in the magnitude and significance of the trends found for climate variables from different sources make these trends plausible. As such, this study presents probably the most convincing regional estimates for the CV area, and to our knowledge, there are no better observations available than used in this study. ERA-40 Reanalysis (Uppala et al., 2005), another well known global Reanalysis was not included in this study, because the ERA-40 is know to be generally less homogeneous than the NCEP-NCAR Reanalysis (e.g. Chen et al., 2008).

With the Santa Rosa meteorological station, which is about 80 km away from the CV, we have chosen among the closest stations to the CV. Since in the tropics air temperature is relatively persistent within horizontal distances (Sobel et al., 2001), we consider a distance of 80 km reasonable. The vertical distance between the station and the glacier terminus can be compensated by using the regionally derived lapse-rate value (0.5 °C/100 m) reported by Urrutia and Vuille (2009).

6.3 Relation between observed climatic trends and glacier changes

The relatively slight negative trend of precipitation and the moderate increase of air temperature found for the CV can not in full explain the observed substantial ice losses. In the following, we therefore try to further discuss and complete the observed changes.

Area and volume changes of a glacier are related to climatic variables through its energy and mass balance. Negative changes in the mass balance of a glacier result either from increased ablation or decreased accumulation, which are mainly determined by precipitation and air temperature. For the tropical and subtropical Andes, Francou et al. (2003) concluded that precipitation and cloud cover changes were minor in the 20th century and it is thus unlikely that decreased accumulation explains the observed glacier retreat in the region. In contrast, they found a positive trend for air temperature and conclude that glacier retreat is mainly caused by increased ablation, rather than decreased accumulation. The trends that are indicated by our data for CV are consistent with these conclusions, and the slight (non-significant) decrease in precipitation we note over the past decades (Fig. 5) is unlikely to account for all the glacier retreat. In the following, we will thus turn our discussion on the effects of climatic changes on the ablation processes.

The most important terms able to significantly influence the surface energy balance of a tropical glacier are net solar radiation (Q_R), net longwave radiation (Q_L) and, to a lesser extent, the turbulent sensible (Q_H) and latent heat fluxes (Q_{LE}), as measured by Hastenrath (1978) for QIC and by Sicart et al. (2005) for Zongo glacier in Bolivia. Air temperature is typically highly correlated to various components of the energy balance. However, as the measurements by Sicart et al. (2008) show, air temperature in the tropics is poorly correlated to net short wave radiation, particularly for short time steps, and is thus a weak index for the energy balance. In relation with Q_R, albedo is another important factor. On tropical high-elevation glaciers, there are different factors that can modify albedo, including changes in precipitation in relation with air temperature (rain or snow) and factors like debris cover, dust and soot. The latter factors are of minor importance at the CV due to its high altitude, and the absence of high rock faces around the glaciers. Moreover, to our knowledge there is no specific long-term albedo information available for the CV. For precipitation only a very slight trend is observed at the operational meteorological stations of SENAMHI (Fig. 5). However, there is a significant air temperature increase observed in both data sets. Using the lapse-rate values of Urrutia and Vuille (2009) to translate the upper-air temperature data to glacier terminus elevation, the mean temperature stays well below 0 °C, and maximum air temperature is well above 0 °C (while minimum air temperature shows no significant trend). Consequently, it can be inferred that the relation between liquid and solid precipitation arriving at the glacier surface has not changed during the past decades and the average albedo has not or only moderately been modified. Therefore, it can be assumed that most of the precipitation still falls in the form of snow, and average albedo is thus only moderately changed by the observed air temperature increase. Nevertheless, Bradley et al. (2009) report an increase in freezing level heights for the Quelccaya Ice Cap, implying that air temperature increase in the future could have a more important effect on albedo and thus on Q_R, as the snowline moves upwards. Bradley et al. (2009) had based their study on an analysis of daily maximum air temperatures only.

In addition to the global mean air temperature increase during the last 150 yr, a significant increase has also been observed for water vapour, another and even more effective Greenhouse Gas (IPCC, 2007). Increased water vapour is mainly observed in the tropopause and in the lower stratosphere (Dessler et al., 2008). Dessler et al. (2008) also found particular high values for regions slightly south of the equator. The CV, located at about 14° S and with glaciers at very high altitudes (between about 4700 and 6384 m a.s.l.), is close to this zone of largest changes in specific humidity. The NCEP/NCAR Reanalysis for the Cusco area shows an increase in specific humidity (q) at the 500 hPa level since 1958, also consistent with the observations and analyses from Dessler et al. (2008). This increase of q can significantly influence Q_{LE}, which would attenuate the typically negative latent heat flux on high altitude tropical glaciers, and in turn make more energy available for melting (e.g. Wagnon et al., 1999). An increase in q leads additionally to an increase in incoming long wave radiation (Ruckstuhl et al., 2007; Ohmura, 2001), which leads often to an increase in air temperature near the surface. Depending on the effective quantity of specific humidity available, an increase in long wave radiation can lead to melting or sublimation and thus to a mass loss of glacier ice. Therefore, we argue here, that the increase in water vapour during the past decades exerted an important control on the massive ice loss observed in the CV, particularly before 2000. This argument is strengthened by the fact that tropical glaciers in general respond relatively rapidly to changes in atmospheric conditions (typically within a few years) because of their usually small sizes (e.g. Bahr et al., 1998). This rapid response time can furthermore also explain the more rapid retreat of glaciers as observed since the 1980s.

7 Conclusions and perspectives

In this study we presented a multi-sources approach allowing the generation of a data baseline for regional glacier and climatic trend analyses in a data scarce mountain area. We assimilated and analyzed a comprehensive data collection of glacier and climate observations for the CV region (Southern Peruvian Andes), which exemplifies a remote, data scarce mountain region, with major socio-economic importance due

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to its water resource. For such regions, there is an increasing demand by decision and policy makers for information about climatic changes, related impacts and future scenarios. Such demands will even increase in the future with regard to ongoing international efforts (e.g. Adaptation Fund (AF) and the new Climate Fund under the United Nations Framework Convention on Climate Change, UNFCCC) for developing and implementing adequate adaptation measures, on regional and local levels.

The trends we found in our study are generally in line with continental and regional trends from other studies. Glacier ice reduction is slightly higher than in other Cordilleras in the region, and higher than e.g. in the European Alps. At the same time, air temperature trends are positive, but weaker than for Europe, while precipitation sums remained about stable. Furthermore, we found an increase of specific humidity for the area of CV, which may explains part of the observed substantial ice loss.

Assuming that the observed climatic trends will continue in future in the CV region the impacts would affect the four seasons differently as outlined in the following and with implications to be considered in any adaption strategy plans: Austral winter (JJA), generally a very dry season would not be much influenced by increasing q, because the large positive radiation balance would be cancelled out by the large negative long wave radiation. For austral spring (SON) and fall (MAM) precipitation events might become more frequent, and it will be critical whether they hit the ground as rain or as snow because of the large albedo difference and its impact on the mass balance. With increased humidity, long wave energy loss would generally be small, but in spring and fall, any assessment remains difficult. For Austral summer (DJF) the picture is different and assessments somewhat simpler. This season is characterized by large precipitation events. With a trend towards even moister austral summers, the long wave radiation balance would be even more often balanced and in combination with clear-sky conditions from time to time (which is possible with convective regimes), short wave radiation would be favoured as melt energy and cause an increase in melt. However, if q increases to very high amounts, it could also lead to increased precipitation (as projected by many GCMs) and tip the system.

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These complex interactions between climate and glaciers also show clearly the need for long-term in-situ measurements in order to better understand the effective ongoing processes and to provide a data baseline that allows for reliable projections of future glacier and runoff evolution. Therefore, in July 2010, a new glacier monitoring network was initiated on two glaciers in the CV, within the frame of the PACC project. Moreover, in May 2011, on one of the glaciers a climate station was installed by SENAMHI. More specific insights on local climate and glacier evolution at CV are thus to be expected in the forthcoming years.

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References

Albert, T. H.: Evaluation of remote sensing techniques for ice-area classification applied to the tropical Quelccaya ice cap, Peru, Polar Geography, 26, 210–226, 2002.

Ames, A., Dolores, S., Valverde, A., Evangelista, C., Javier, D., Ganwini, W., and Zuniga, J.: Glacier inventory of Peru, Part I. Hidrandina S.A. Huaraz, Peru, 1998.

ASTER Validation Team: ASTER global DEM validation summary report, Validation Team: METI/ERSDAC, NASA/LPDAAC, USGS/EROS, 2009: ASTER Global DEM Validation, Summary Report, available at: https://lpdaac.usgs.gov, 2009.

Auer, I., Böhm, R., Jurkovic, A., Lipa, W., Orlik, A., Potzmann, R., Schöner, W., Ungersböck, M., Matulla, C., Briffa, K., Jones, P., Efthymiadis, D., Brunetti, M., Nanni, T., Maugeri, M., Mercalli, L., Mestre, O., Moisselin, J.-M., Begert, M., Müller-Westermeier, G., Kveton, V., Bochnicek, O., Stastny, P., Lapin, M., Szalai, S., Szentimrey, T., Cegnar, T., Dolinar, M., Gajic-Capka, M., Zaninovic, K., Majstorovic, Z., and Nieplova, E.: HISTALP – historical instrumental climatological surface time series of the Greater Alpine Region, Internat. J. Clim., 27, 17–46, 2007.

Bahr, D. B., Meier, M. F., and Peckham, S. D.: The physical basis of glacier volume-area scaling, J. Geophys. Res, 102, 355–362, 1997.

Bahr, D. B., Pfeffer, W. T., Sassolas, C., and Meier, M. F.: Response time of glaciers as a function of size and mass balance: I. Theory, J. Geophys. Res., 103, 9777–9782, 1998.
Barnett, T. P., Adam, J. C., and Lettenmaier, D. P.: Potential impacts of a warming climate on water availability in snow-dominated regions, Nature, 438, 303–309, 2005.
Begert, M., Schlegel, T., and Kirchhofer, W.: Homogeneous Temperature and Precipitation Series of Switzerland from 1864 to 2000, Int. J. Climate, 25, 65–80, 2005.
Bengtsson, L. and Shukla, J.: Integration of Space and In Situ Observations to Study Global Climate Change, B. Am. Meteorol. Soc, 69, 1130–1143, 1988.
Bengtsson, L., Hagemann, S., and Hodges, K. I.: Can climate trends be calculated from re-analysis data?, J. Geophys. Res., 109, D11111, doi:10.1029/2004JD004536, 2004.
Binder, D., Bruckl, E., Roch, K. H., Behm, M., Schoner, W., and Hynek, B.: Determination of total ice volume and ice-thickness distribution of two glaciers in the Hohe Tauern region, Eastern Alps, from GPR data, Ann. Glaciol., 50, 71–79, 2009.
Bradley, R. S., Vuille, M., Diaz, H. F., and Vergara, W.: Climate Change: Threats to Water Supplies in the Tropical Andes, Science, 312, 1755–1756 doi:10.1126/science.1128087, 2006.
Bradley, R. S., Keimig, F. T., Diaz, H. F., and Hardy, D. R.: Recent changes in freezing level heights in the Tropics with implications for the deglacierization of high mountain regions, Geophys. Res. Lett., 36, L15703, doi:10.1029/2009GL038826, 2009.
Carey, M.: Living and dying with glaciers: people's historical vulnerability to avalanches and outburst floods in Peru, Global Planet. Change, 47, 122–134, 2005.
Chen, J., Del Genio, A. D., Carlson, B. E., and Bosilovich, M. G.: The spatiotemporal structure of twentieth-century climate variations in observations and reanalyses. Part I: Long-term trend, J. Climate, 21, 2611–2633, doi:10.1175/2007JCLI2011.1, 2008.
Dessler, A. E., Zhang, Z., und Yang, P.: Water-vapor climate feedback inferred from climate fluctuations, 2003–2008, Geophys. Res. Lett., 35, L20704, doi:10.1029/2008GL035333, 2008.
Farinotti, D., Huss, M., Bauder, A., Funk, M., and Truffer, M.: A method to estimate the ice volume and ice-thickness distribution of alpine glaciers, J. Glaciol., 55, 422–430, 2009.
Falvey, M. and Garreaud, R.: Regional cooling in a warming world: Recent temperature trends in the SE Pacific and along the west coast of subtropical South America (1979–2006), J. Geophys. Res., 114, D04102, doi:10.1029/2008JD010519, 2009.
Francou, B., Vuille, M., Wagnon, P., Mendoza, J., and Sicart, J. E.: Tropical climate change recorded by a glacier of the central Andes during the last decades of the 20th century: Chacaltaya, Bolivia, 16° S, J. Geophys. Res., 108, 4154, doi:10.1029/2002JD002959, 2003.

Garreaud, R. D.: The Andes climate and weather, Adv. Geosci., 22, 3–11, doi:10.5194/adgeo-22-3-2009, 2009.
Georges, C.: 20th-century glacier fluctuations in the Tropical C. Blanca, Peru, Arct. Antarct. Alp. Res., 36, 100–107, 2004.
Haeberli, W. and Hoelzle, M.: Application of inventory data for estimating characteristics of and regional climate-change effects on mountain glaciers: a pilot study with the European Alps, Ann. Glaciol., 21, 206–212, 1995.
Hastenrath, S.: Heat-budget measurements on the Quelccaya ice cap, Peruvian Andes, J. Glaciol., 20, 85–97, 1978.
Huggel, C., Haeberli, W., Kääb, A., Hoelzle, M., Ayros, E., and Portocarrero, C.: Assessment of glacier hazards and glacier runoff for different climate scenarios based on remote sensing data: a case study for a hydropower plant in the Peruvian Andes, in: Proceedings of EARSeL-LISSIG-Workshop Observing our Cryosphere from Space, 22–33, 2003.
IPCC: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2007.
Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R., and Joseph, D.: The NCEP/NCAR 40-Year Reanalysis Project, B. Am. Meteorol. Soc., 77, 437–471, 1996.
Kaser, G.: Glacier-climate interaction at low latitudes, J. Glaciol., 47, 195–204, 2001.
Kaser, G. and Osmaston, H.: Tropical glaciers, Cambridge University Press, 2002.
Kaser, G., Juen, I., Georges, C., Gomez, J., Tamayo, W.: The impact of glaciers on the runoff and the reconstruction of mass balance history from hydrological data in the tropical Cordillera Blanca, Peru, J. Hydrol., 282, 130–144, 2003.
Linsbauer, A., Paul, F., Hoelzle, M., Frey, H., and Haeberli, W.: The Swiss Alps without glaciers – a GIS-based modelling approach for reconstruction of glacier beds, Proceedings of Geomorphometry 2009, Zurich, Switzerland, 31 August–2 September 2009, 243–247, 2009.
Lüthi, M. P., Bauder, A., and Funk, M.: Volume change reconstruction of Swiss glaciers from length change data, J. Geophys. Res., 115, F04022, doi:10.1029/2010JF001695, 2010.

Mark, B. G., Seltzer, G. O., Rodbell, D. T., and Goodman, A. Y.: Rates of deglaciation during the last glaciation and Holocene in the C. Vilcanota-Quelccaya Ice Cap region, southeastern Peru, Quaternary Res., 57, 287–298, 2002.
Mark, B. and Seltzer, G.: Evaluation of recent glacier recession in the Cordillera Blanca, Peru (AD 1962–1999): spatial distribution of mass loss and climatic forcing, Quaternary Sci. Rev., 24, 2265–2280, 2005.
Meister, I.: Modelling and analysis of the subglacial topography of Jostedalsbreen, Norway, Master thesis, Department of Geogprahy, University of Zurich, 2010.
Morales-Arnao, B. and Hastenrath, S.: Glaciers of Peru, in: Satellite Image Atlas of Glaciers of the World, edited by: Williams Jr., R. S. and Ferrigno, J. G., US Geological Survey Professional Paper 1386-I-4, 151–179, 1999.
Ohmura, A.: Physical basis for the temperature-based melt-index method, J. Appl. Meteorol., 40, 753–761, 2001.
Paltridge, G., Arking, A., and Pook, M.: Trends in middle- and upper-level tropospheric humidity from NCEP reanalysis data, Theor. Appl. Climatol., 98, 351–359, doi:10.1007/s00704-009-0117-x, 2009.
Paterson, W. S. B.: The Physics of Glaciers, Pergamon, New York, 1994.
Paul, F., Kaab, A., Maisch, M., Kellenberger, T., and Haeberli, W.: The new remote-sensing-derived Swiss glacier inventory, I. Methods. Annals Glaciology, 34, 355–361, 2002.
Peduzzi, P., Herold, C., and Silverio, W.: Assessing high altitude glacier thickness, volume and area changes using field, GIS and remote sensing techniques: the case of Nevado Coropuna (Peru), The Cryosphere, 4, 313–323, doi:10.5194/tc-4-313-2010, 2010.
Rabus, B., Eineder, M., Roth, A., and Bamler, R.: The shuttle radar topography mission – a new class of digital elevation models acquired by spaceborne radar, ISPRS J. Photogramm., 57, 241–262, 2003.
Racoviteanu, A. E., Manley, W. F., Arnaud, Y., and Williams, M. W.: Evaluating digital elevation models for glaciologic applications: An example from Nevado Coropuna, Peruvian Andes, Global Planet. Change, 59, 110–125, 2007.
Racoviteanu, A. E., Arnaud, Y., Williams, M. W., and Ordonez, J.: Decadal changes in glacier parameters in the C. Blanca, Peru, derived from remote sensing, J. Glaciol., 54, 499–510, 2008.
Raup, B., Kääb, A., Kargel, J. S., Bishop, M. P., Hamilton, G., Lee, E., Paul, F., Rau, F., Soltesz, D., Khalsa, S. J., Beedle, M., and Helm, C.: Remote sensing and GIS technology in the

Global Land Ice Measurements from Space (GLIMS) project, Comput. Geosci., 33, 104–125, 2007.
Reuter, H., Nelson, A., Strobl, P., Mehl, W., and Jarvis, A.: A first assessment of Aster GDEM tiles for absolute accuracy, relative accuracy and terrain parameters, in: Geoscience and Remote Sensing Symposium, 2009 IEEE International, IGARSS 2009, V-240–V-243, 2009.
Ruckstuhl, C., Philipona, R., Morland, J., and Ohmura, A.: Observed relationship between surface specific humidity, integrated water vapor, and longwave downward radiation at different altitudes, J. Geophys. Res., 112, D03302, doi:10.1029/2006JD007850, 2007.
Salzmann, N., Huggel, C., Calanca, P., Díaz, A., Jonas, T., Jurt, C., Konzelmann, T., Lagos, P., Rohrer, M., Silverio, W., and Zappa, M.: Integrated assessment and adaptation to climate change impacts in the Peruvian Andes, Adv. Geosci., 22, 35–39, doi:10.5194/adgeo-22-35-2009, 2009.
Schwarb, M., Acuña, D., Konzelmann, Th., Rohrer, M., Salzmann, N., Serpa Lopez, B., and Silvestre, E.: A data portal for regional climatic trend analysis in a Peruvian High Andes region, Adv. Sci. Res., 6, 219–226, doi:10.5194/asr-6-219-2011, 2011.
Sicart, J. E., Wagnon, P., and Ribstein, P.: Atmospheric controls of heat balance of Zongo Glacier. 16° S Bolivia, J. Geophys. Res., 110, D12106, doi:10.1029/2004JD005732, 2005.
Sicart, J. E., Hock, R., and Six, D.: Glacier melt, air temperature, and energy balance in different climates: The Bolivian Tropics, the French Alps, and northern Sweden, J. Geophys. Res., 113, D24113, doi:10.1029/2008JD010406, 2008.
Silverio, W. and Jaquet, J. M.: Glacial cover mapping (1987–1996) of the C. Blanca (Peru) using satellite imagery, Remote Sens. Environ., 95, 342–350, 2005.
Sobel, A. H., Nilsson, J., and Polvani, L. M.: The weak temperature gradient approximation and balanced tropical moisture waves, J. Atmos. Sci., 58, 3650–3665, 2001.
Thompson, L. G., Hastenrath, S., and Arnao, B. M.: Climatic ice core records from the tropical Quelccaya Ice Cap, Science, 203, 1240–1243, doi:10.1126/science.203.4386.1240, 1979.
Thompson, L. G., Bolzan, J. F., Brecher, H. H., Kruss, P. D., Mosley-Thompson, E., and Jezek, K. C.: Geophysical investigations of the tropical Quelccaya ice cap, Peru, J. Glaciol., 28, 57–69, 1982.
Thompson, L. G., Mosley-Thompson, E., and Morales Arnao, B. M.: El Niño-Southern Oscillation events recorded in the stratigraphy of the tropical Quelccaya ice cap, Peru, Science, 226, 50–53, doi:10.1126/science.226.4670.50, 1984.
Thompson, L. G., Mosley-Thompson, E., Bolzan, J. F., and Koci, B. R.: A 1500-year record of

tropical precipitation in ice cores from the Quelccaya ice cap, Peru, Science, 229, 971–973, doi:10.1126/science.229.4717.971, 1985.
Uppala, S. M., Kållberg, P. W., Simmons, A. J., Andrae, U., Bechtold, V. D. C., Fiorino, M., Gibson, J. K., Haseler, J., Hernandez, A., Kelly, G. A., Li, X., Onogi, K., Saarinen, S., Sokka, N., Allan, R. P., Andersson, E., Arpe, K., Balmaseda, M. A., Beljaars, A. C. M., Van De Berg, L., Bidlot, J., Bormann, N., Caires, S., Chevallier, F., Dethof, A., Dragosavac, M., Fisher, M., Fuentes, M., Hagemann, S., Hólm, E., Hoskins, B. J., Isaksen, L., Janssen, P. A. E. M., Jenne, R., McNally, A. P., Mahfouf, J.-F., Morcrette, J.-J., Rayner, N. A., Saunders, R. W., Simon, P., Sterl, A., Trenberth, K. E., Untch, A., Vasiljevic, D., Viterbo, P., and Woollen, J.: The ERA-40 re-analysis, Q. J. Roy. Meteor. Soc., 131, 2961–3012, 2005.
Urrutia, R. and Vuille, M.: Climate change projections for the tropical Andes using a regional climate model: Temperature and precipitation simulations for the end of the 21st century, J. Geophys. Res., 114, D02108, doi:10.1029/2008JD011021, 2009.
Vergara, W., Deeb, A., Valencia, A., Bradley, R., Francou, B., Zarzar, A., Grünwaldt, A., and Haeussling, S.: Economic impacts of rapid glacier retreat in the Andes, Eos Trans. AGU, 88, 261, doi:10.1029/2007EO250001, 2007.
Vey, S., Dietrich, R., Rülke, A., and Fritsche, M.: Validation of Precipitable Water Vapor within the NCEP/DOE Reanalysis Using Global GPS Observations from One Decade, J. Climate, 23, 1675–1695, doi:10.1175/2009JCLI2787.1, 2009.
Vuille, M., Bradley, R. S., Werner, M., and Keimig, F.: 20th Century Climate Change in the Tropical Andes: Observations and Model Results, Climatic Change, 59, 75–99, 2003.
Vuille, M., Francou, B., Wagnon, P., Juen, I., Kaser, G., Mark, B. G., and Bradley, R. S.: Climate change and tropical Andean glaciers: Past, present and future, Earth Sci. Rev., 89, 79–96, 2008.
Wagnon, P., Ribstein, P., Kaser, G., and Berton, P.: Energy balance and runoff seasonality of a Bolivian glacier, Global Planet. Change, 22, 49–58, 1999.
WGMS: Glacier Mass Balance Bulletin No. 10 (2006–2007), edited by: Haeberli, W., Gärtner-Roer, I., Hoelzle, M., Paul, F., and Zemp, M., ICSU (WDS)/IUGG (IACS)/UNEP/UNESCO/WMO, World Glacier Monitoring Service, Zurich, Switzerland, 96 pp., 2009.
Zemp, M., Haeberli, W., Hoelzle, M., and Paul, F.: Alpine glaciers to disappear within decades?, Geophys. Res. Lett., 33, L13504, doi:10.1029/2006GL026319, 2006.

Table 1. Results of glacier mapping and ice volume estimates. The 2006 volume numbers marked with * are lowermost and uppermost estimates, i.e., by assessing a 20 % thickness reduction for the 1 bar case, and a 10 % thickness reduction for the 1.2 bar case, thus encompassing the uncertainties related to basal shear stress and reduction in glacier thickness between 1962 and 2006.

Year	Glacier area (km^2)	Percent of initial area (%)	Total glacier volume (km^3, $\tau = 1$ bar)	Total glacier volume (km^3, $\tau = 1.2$ bar)
1962	440	100	17.0	20.4
1985	444	101		
1996	344	78		
2006	297	68	9.2*	12.4*

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Table 2. Loss of glacier area between 1962 and 2009 for QIC and Qori Kalis, an outlet glacier of the ice cap.

Year	Quelccaya Ice Cap area (km^2)	Percent of initial area (%)	Qori Kalis glacier area (km^2)	Percent of initial area (%)
1962	57.5	100		
1975	56.2	98	0.92	100
1985	55.7	97	0.84	91
1991	47.9	83	0.76	83
2000	45.9	80	0.59	64
2004	45.4	79	0.58	63
2006	44.2	77	0.53	58
2008	42.8	74	0.49	53
2009	42.8	74	0.49	53

Table 3. Minimum air temperature, Santa Rosa station (partly reconstr.).

year	p-value	trend magnitude [˚C]
DJF	0.005	0.7
MAM	0.95	0.06
JJA	0.46	−0.36
SON	0.014	1.43

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Table 4. Maximum air temperature, Santa Rosa station (partly reconstr.).

year	p-value	trend magnitude [°C]
DJF	0.056	0.7
MAM	0.001	0.95
JJA	0.002	0.9
SON	0.001	0.7

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Table 5. Monthly mean air temperature, NCEP/NCAR Reanalysis.

year	p-value	trend magnitude [˚C]
DJF	0.0	0.88
MAM	0.0	0.73
JJA	0.0	0.8
SON	0.0	0.94

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Table 6. Precipitation sums, Santa Rosa station (partly reconstr.).

year	p-value	trend magnitude [mm]
DJF	0.09	−83
MAM	0.15	−56
JJA	0.15	−17
SON	0.043	−70

Table 7. Specific humidity, NCEP/NCAR Reanalysis.

year	p-value	trend magnitude [$g\,kg^{-1}$]
DJF	0.0	0.5
MAM	0.001	0.36
JJA	0.006	0.28
SON	0.0	0.5

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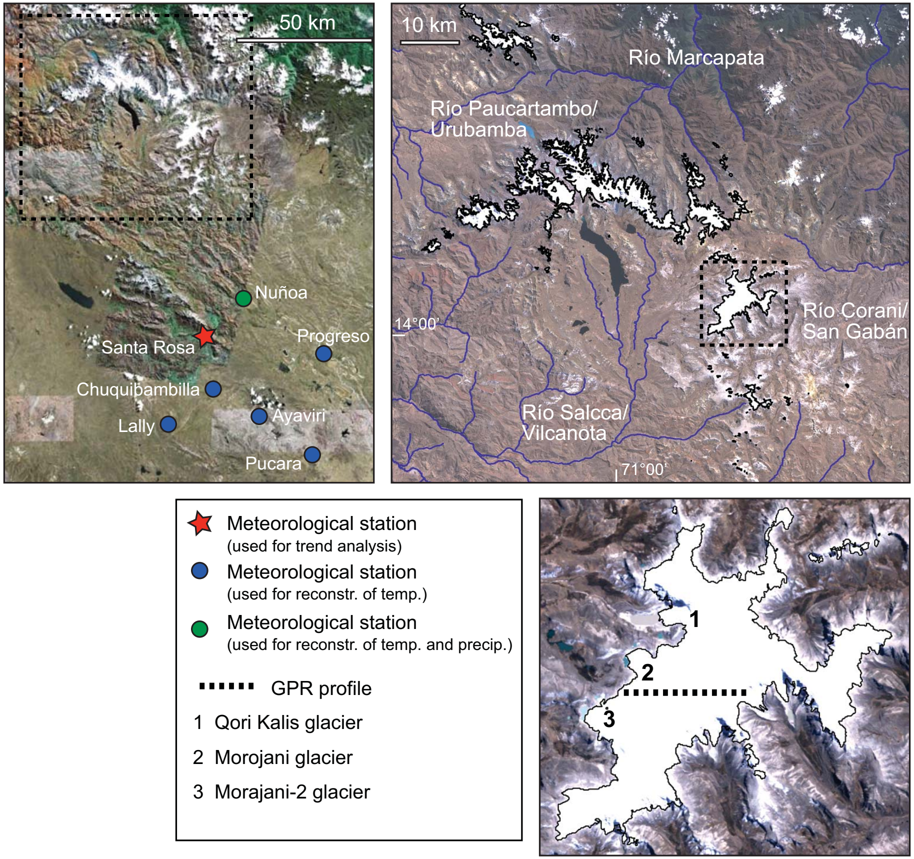

Fig. 1. Upper left: overview of study site; upper right: satellite view on the CV (Landsat-TM5, 4 August 2006) with major river catchments indicated. The glacier outlines of 2006 are marked with a black line. Lower right: a close-up of the QIC with the dashed line indicating the location of the GPR profile taken in 2008.

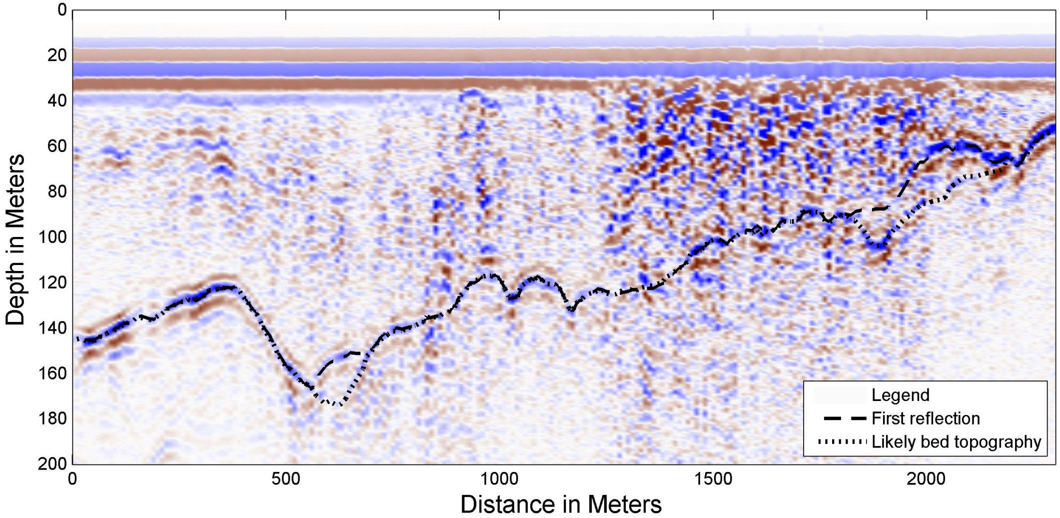

Fig. 2. Ground Penetrating Radar (GPR) profile taken on QIC in 2008 along an east-west profile. The exact location is indicated in Fig. 1.

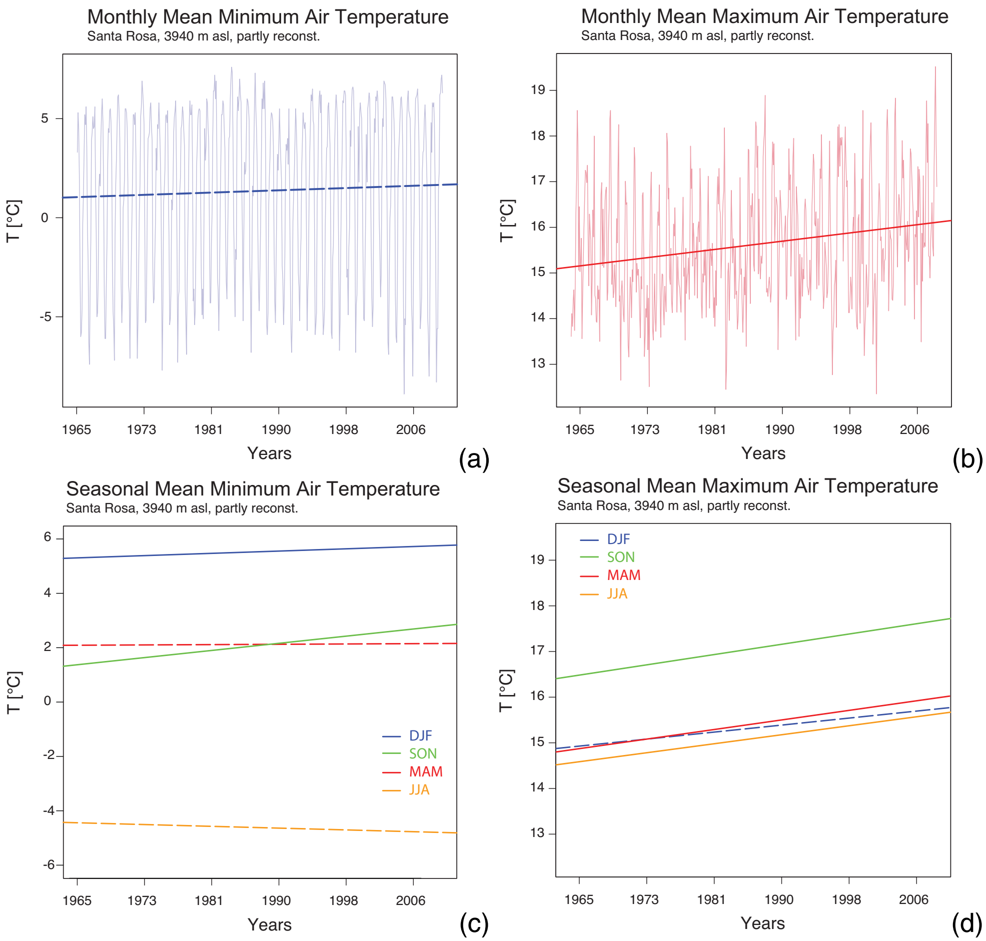

Fig. 3. Monthly minimum **(a)** and maximum **(b)** air temperature for Santa Rosa station and the seasonal trends **(c, d)**. Dashed lines indicate where trend is not significant (cf. also Tables 3 and 4).

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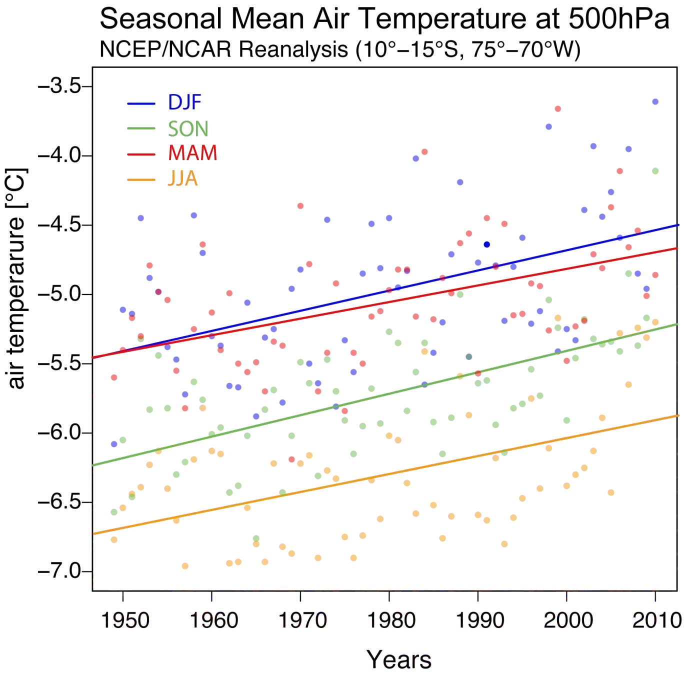

Fig. 4. Linear trends for mean seasonal air temperature at 500 hPa level from NCEP/NCAR Reanalysis. Dashed lines indicate where trends are not significant (cf. Table 5).

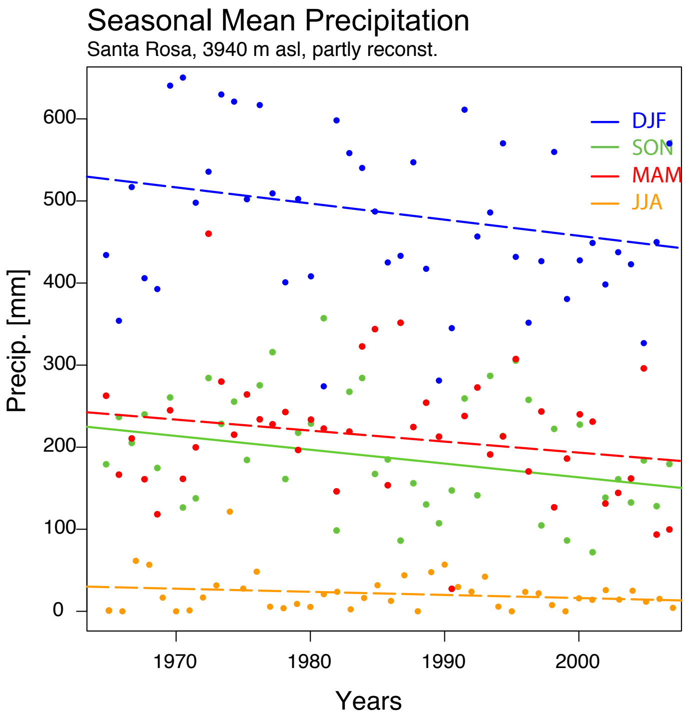

Fig. 5. Linear trend for seasonal precipitation sums from the station Santa Rosa. Dashed lines indicate where the trends are not significant (cf. Table 6).

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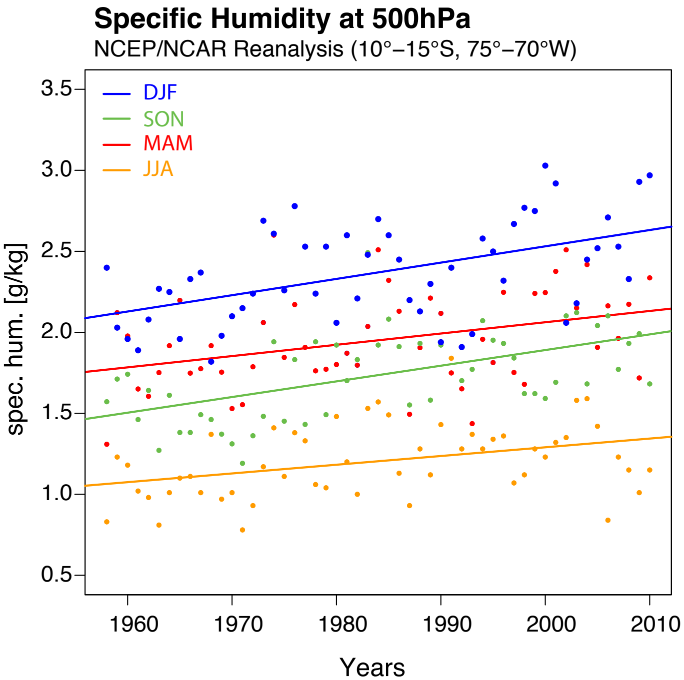

Fig. 6. Linear trend for seasonal mean of specific humidity from NCEP/NCAR Reanalysis. Dashed lines indicate where the trends are not significant (cf. Table 7).

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